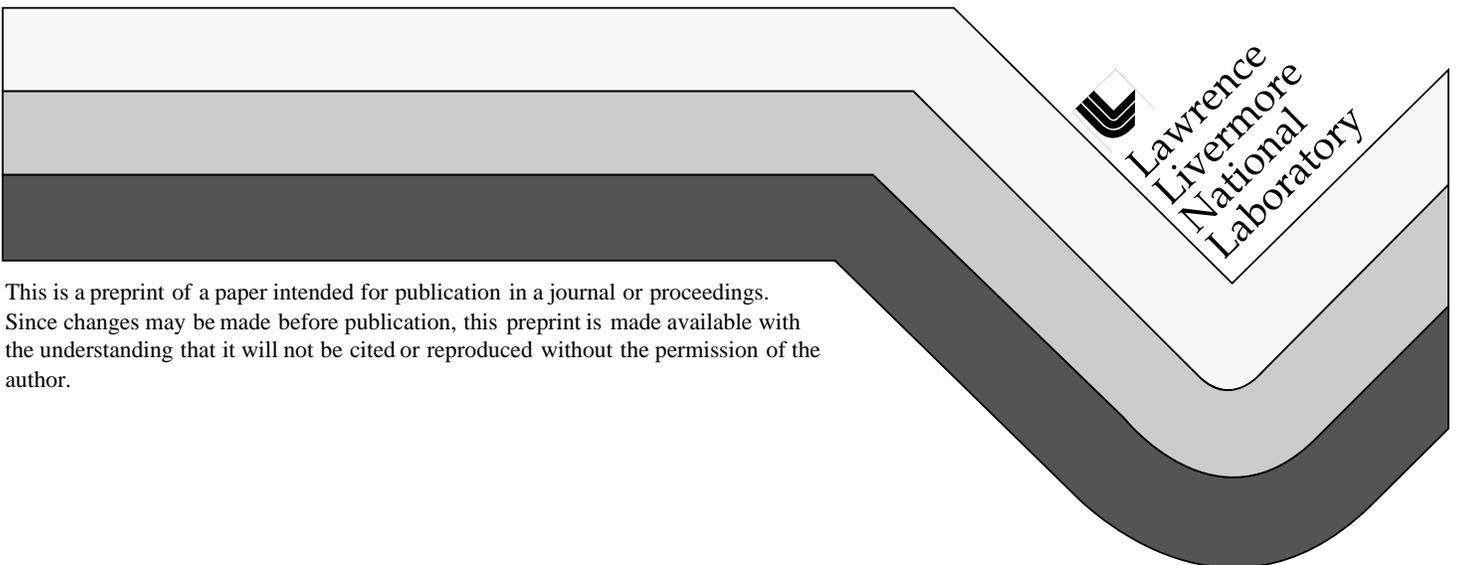


A Relic Neutrino Detector

C. Hagmann

This paper was prepared for submittal to the
COSMO-98
Asilomar, CA
November 15-20, 1998

January 27, 1999



This is a preprint of a paper intended for publication in a journal or proceedings.
Since changes may be made before publication, this preprint is made available with
the understanding that it will not be cited or reproduced without the permission of the
author.

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

A Relic Neutrino Detector

C. Hagmann

*Lawrence Livermore National Laboratory
7000 East Avenue, Livermore, CA 94550*

Abstract. Probably the most promising way of detecting cosmic neutrinos is measuring the mechanical force exerted by elastic scattering of cosmic neutrinos from macroscopic targets. The expected acceleration is $\sim 10^{-23}\text{cm/s}^2$ for Dirac neutrinos of mass $\sim 10\text{ eV}$ and local density $\sim 10^7/\text{cm}^3$. A novel torsion balance design is presented, which addresses the sensitivity-limiting factors of existing balances, such as seismic and thermal noise, and angular readout resolution and stability.

INTRODUCTION

The standard Big Bang model predicts a universal background of relic neutrinos, with an average density of $\sim 100/\text{cm}^3$ per flavor. Relic neutrinos of mass $\gg 10^{-3}\text{ eV}$ would be nonrelativistic today, and contribute to the cosmological energy density an amount $\Omega_\nu \sim \sum_i m_{\nu_i}/(90h^2\text{eV})$, where $h \simeq 0.65$ is the Hubble expansion rate in units of $100\text{ km}/(\text{s Mpc})$. Massive neutrinos are a natural candidate for the hot component in currently favored “Mixed Hot+Cold Dark Matter (HCDM)” [1] models of galaxy formation. In this scenario, neutrinos would contribute $\sim 20\%$, and CDM (e.g. Wimps and axions) the remainder of the dark matter. Nonrelativistic neutrinos would be clustered around galaxies and move with a typical velocity $v \sim 300\text{ km/s}$. The Pauli principle [2] restricts the local neutrino number density to $n_\nu \lesssim 2 \times 10^6\text{cm}^{-3} (v_{\text{max}}/10^{-3}c)^3 \sum_i (m_{\nu_i}/10\text{eV})^3$. The detection of relic neutrinos is hindered by the extremely small cross sections and energy deposits expected from interactions with electrons and nucleons. Past proposals have focused on detecting the mechanical force on macroscopic targets due to the “neutrino wind”. Here, spatial coherence increases the cross section of targets smaller than the neutrino wavelength $\lambda_\nu \sim 100\text{ }\mu\text{m}(10\text{ eV}/m_\nu)$. In the nonrelativistic limit, one must distinguish between Majorana and Dirac neutrinos. For Dirac μ or τ neutrinos, the cross section is dominated by the vector neutral current contribution $\sigma_D = (G_F^2 m_\nu^2/8\pi)N_n^2 = 2 \times 10^{-55}\text{cm}^2(m_\nu/10\text{ eV})^2 N_n^2$, where N_n is the number of neutrons in the target of size $\lesssim \lambda_\nu/2\pi$. For Majorana neutrinos, the vector contribution is suppressed by a factor $(v/c)^2$. The Sun’s peculiar motion through the galactic halo will produce a wind force, whose direction is mod-

ulated by the Earth's rotation. For Dirac neutrinos, the acceleration of a target of density ρ and radius $\lambda_\nu/2\pi$ is [3] $a = 8 \times 10^{-24} \text{cm/s}^2 ((A - Z)/A)^2 (v_{\text{sun}}/10^{-3}c)^2 (n_\nu/10^7 \text{cm}^{-3}) (\rho/20 \text{gcm}^{-3})$ and is independent of m_ν . A harmonic oscillator driven by the neutrino wind on resonance would experience a displacement amplitude of $\Delta x \simeq 10^{-15} \text{cm}(\tau/\text{day})$. A target of size $\gg \lambda_\nu$ can be assembled, while avoiding destructive interference, by using foam-like or laminated materials [3]. Alternatively, grains of size $\sim \lambda_\nu$ could be randomly embedded in a low density host material.

PROPOSED DETECTOR

At present, the most sensitive detector of small forces is the ‘‘Cavendish’’ torsion balance, which has been widely used for measurements of G , searches for new forces, and tests of the equivalence principle. A typical arrangement consists of a dumbbell-shaped test mass suspended by a tungsten fiber. The angular deflection is read out with an optical lever. The most serious noise backgrounds are 1. thermal noise, 2. seismic noise, 3. time-varying gravity gradients. The smallest measurable acceleration is $\sim 10^{-12} \text{cm/s}^2$ [4]. Several improvements seem possible: Thermal noise can be decreased by lowering the temperature and by employing a low dissipation (high- Q) suspension, as seen from the expression for the thermal noise acceleration [5] $a_{\text{th}} = 2 \times 10^{-23} \text{cm/s}^2 (T/\text{K})^{1/2} (1\text{day}/\tau_0)^{1/2} (10^6 \text{s}/\tau)^{1/2} (10^{16}/Q)^{1/2}$, where τ is the measurement time, τ_0 is the oscillator period, and T is the operating temperature. A promising low-dissipation suspension method uses the Meissner effect. Niobium or NbTi based suspensions have been employed in gravimeters, gyros, and gravitational wave antennas. Generally, the magnetic field applied to the superconductor is limited to $\lesssim 0.2\text{T}$ to avoid flux penetration or loss of superconductivity. A remaining problem is flux creep noise and dissipation because of incomplete flux expulsion. An alternative method would employ a passive persistent-mode superconducting magnet floating above a fixed suspension magnet as shown in Fig. 1. This allows a much higher lifting force because the critical field of NbTi wire is several T. Moreover, the flux lines are strongly pinned by artificial wire defects, leading to a small field decay rate of $\dot{B}/B \sim 10^{-8}/\text{hour}$. The cylindrical symmetry of the suspension magnets allows a very long rotational oscillation period, which can be matched to the diurnally varying neutrino wind by applying a suitable restoring force. The effects of seismic noise and gravity gradients can be reduced with a highly symmetric target (see Fig. 1). With the c.m. of the target centered below the suspension support, the leading order gravitational torques arise from the dipole and quadrupole moments of the target which need to be minimized by balancing. Braginsky et.al. [6] have given estimates of the seismic power spectra for vertical and horizontal, and rotational seismic modes. For example, the horizontal acceleration at $\omega \sim 10^{-4} \text{s}^{-1}$ is $a \sim 10^{-12} \text{cm/s}^2 (\Lambda/100 \text{km})(10^6/\tau)^{-1/2}$, where Λ is the seismic wavelength. Hence, the coupling of this mode to the wanted rotational mode of the torsion oscillator must be made very small. Especially worrisome is rotational seismic noise which will directly mask the signal and needs to be

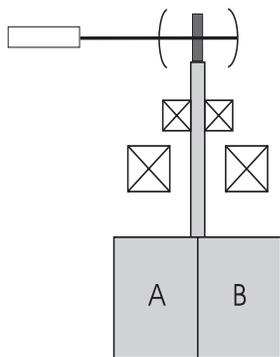


FIGURE 1. Schematic diagram of the torsion oscillator. The target consists of two hemicylindrical masses with similar densities but different neutrino cross sections. The mass is suspended by a “magnetic hook” consisting of a superconducting magnet in persistent mode floating above a stationary magnet. The rotation angle is read out by measuring the resonance frequency of a tunable Fabry-Perot cavity with a laser.

compensated. The proposed angular rotation readout is composed of a parametric transducer, which converts the angle to an optical frequency. As shown in Fig. 2, the transducer consists of a high- Q optical cavity of length l , tuned by a Brewster-angled low loss dielectric plate of thickness d . A cavity finesse $F \simeq 10^5$ should be obtainable with dielectric mirrors for the Gaussian TEM_{00p} modes. The frequency tuning sensitivity is $\Delta f/f \sim (d/l)\Delta\theta$ yielding a resolution of $\sim 10^{-14}\text{rad/Hz}$. The angular measurement precision depends on the number of photons N and laser wavelength λ via $\Delta\theta \sim \lambda/(dF\sqrt{N})$. This is a factor $\simeq F$ better than the optical lever for the same laser power. Cryogenic optical resonators have excellent long-term stability and have been proposed as secondary frequency standards. The measured frequency drifts range from $\sim 1\text{Hz}$ over minutes to $\sim 100\text{Hz}$ over days [7]. For the measurement of the rotation angle, a stable reference frequency will be required. This can be implemented using a laser locked to a second (untuned) cavity. Because of its symmetry, the described angle readout has high immunity against lateral, tilt, and vertical seismic noise, but couples to rotational noise. A possible solution would be to suspend the target as well as the optical cavity in order to suppress the common rotation mode. Additional background forces will arise from gas collisions, cosmic ray hits, and radioactivity, etc., resulting in a Brownian motion of the target. The equivalent acceleration is $a \sim (\bar{p}/m)(\Gamma/\tau)^{1/2}$, where \bar{p} is the average momentum transfer, Γ is the collision or decay rate, and m is the test mass. The residual gas pressure must hence be kept very low by cryopumping and the use of getters. The cosmic muon flux at sea level is $\simeq 100/(\text{m}^2\text{s})$ and can be reduced by going underground. Further disturbing forces may be caused by time-varying electric and magnetic background fields, which can be shielded with superconductors. Thermal radiation and radiometric effects are much reduced by a temperature controlled cryogenic environment. Finally, there is a fundamental

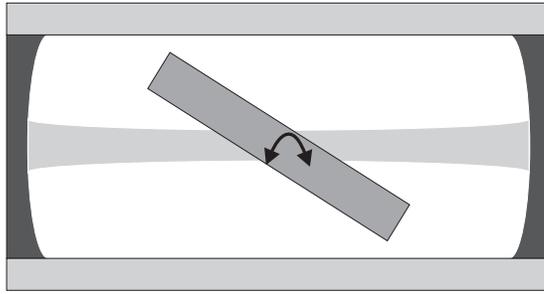


FIGURE 2. Topview diagram of the tunable high- Q optical cavity. The cavity is operated in the Gaussian TEM_{00p} mode. A narrow linewidth ~ 100 kHz is achieved with high reflectivity mirrors and a low-loss dielectric Brewster-angled plate.

limit imposed by the uncertainty principle, with a minimum measurable acceleration given by $a_{SQL} = 5 \times 10^{-24} \text{cm/s}^2 (10 \text{kg}/m)^{1/2} (1 \text{day}/\tau_0)^{1/2} (10^6 \text{s}/\tau)$. In our proposed position readout, the disturbing back action force arises from spatial fluctuations in the photon flux passing through the central tuning plate. There is hope that relic neutrinos will be detected in the laboratory early in the next century, especially if they have masses in the eV range and are of Dirac type. The most viable way seems to be a much improved torsion balance operating underground. Naturally, a slightly modified balance could be used to test the equivalence principle [8] and to search for new macroscopic forces [4].

ACKNOWLEDGEMENTS

This research was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

REFERENCES

1. Primack J., *Science* **280**, 1398 (1998); Gawiser E., and Silk J., *ibid.*, 1405 (1998).
2. Tremaine S., and Gunn J.E., *Phys. Rev. Lett.* **42**, 407 (1979).
3. Shvartsman V.F., Braginski V.B., Gershtein S.S., Zel'dovich Y.B., and Khlopov M.Y., *JETP Lett.* **36**, 277 (1982); Smith P.F., and Lewin J.D., *Phys. Lett.* **B127**, 185 (1983).
4. Adelberger E., Heckel B., Stubbs C., and Rogers W., *Annu. Rev. Nucl. Part. Sci.* **41**, 269 (1991).
5. Braginsky V., and Manukin A., *Measurements of Weak Forces in Physics Experiments*, Chicago: The University of Chicago Press, 1977.
6. V. Braginsky, C. Caves, and K. Thorne, *Phys. Rev.* **D15**, 2047 (1977).
7. Seel S., Storz R., Ruoso G., Mlynek J., and Schiller S., *Phys. Rev. Lett.* **78**, 4741 (1997).
8. Roll P., Krotkov R., and Dicke R., *Ann. Phys. (N.Y.)* **26**, 442 (1964); Braginsky V., and Panov V., *JETP Lett.* **34**, 463 (1972).